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Space Transportation Systems Life Cycle Cost Assessment and Control

John W. Robinson¹

The Boeing Company, Huntington Beach, California, 90740

Russell E. Rhodes² and Edgar Zapata³

Kennedy Space Center, Florida 32899

Daniel J. H. Levack⁴

Pratt & Whitney Rocketdyne, Canoga Park, California, 91309

Benjamin B. Donahue⁵

The Boeing Company, Huntsville, Alabama, 35806

and

William Knuth⁶

Orbital Technologies Corporation, Madison, Wisconsin, 53117

Civil and military applications of space transportation have been pursued for just over 50 years and there has been, and still is, a need for safe, dependable, affordable, and sustainable space transportation systems. Fully expendable and partially reusable space transportation systems have been developed and put in operation that have not adequately achieved this need. Access to space is technically achievable, but presently very expensive and will remain so until there is a breakthrough in the way we do business. Since 1991 the national Space Propulsion Synergy Team (SPST) has reviewed and assessed the lessons learned from the major U.S. space programs of the past decades focusing on what has been learned from the assessment and control of Life Cycle Cost (LCC) from these systems. This paper presents the results of a selected number of studies and analyses that have been conducted by the SPST addressing the need, as well as the solutions, for improvement in LCC. The major emphasis of the SPST processes is on developing the space transportation system requirements first (up front). These requirements must include both the usual system flight performance requirements and also the system functional requirements, including the infrastructure on Earth's surface, in-space and on the Moon and Mars surfaces to determine LCC. This paper describes the development of specific innovative engineering and management approaches and processes. This includes a focus on flight hardware maturity for reliability, ground operations approaches, and business processes between contractor and government organizations. A major change in program/project cost control is being proposed by the SPST to achieve a sustainable space transportation system LCC - controlling cost as a program metric in addition to the existing practice of controlling performance and weight. Without a firm requirement and methodically structured cost control, it is unlikely that an affordable and sustainable space transportation system LCC will ever be achieved.

¹ Principal Engineer/Scientist, Propulsion Engineering, 5301 Bolsa Avenue / H013-C313, AIAA Associate Fellow

² AST, Technical Management, Engineering Directorate Design & Development Eng Div Sys Engineering & Integration Br, Kennedy Space Center, Florida/NE-D2, and AIAA Senior Member...

³ Operations Analysis, Modeling & Simulation, Engineering Directorate Design & Development Eng Div Sys Engineering & Integration Br, Kennedy Space Center, Florida/ Code IT-C1.

⁴ Program Manager, Advanced Programs, P O. Box 7922 / MS RFB19, AIAA Member

⁵ System Engineer, Advanced Systems Group, 950 Explorer Blvd, MS JV- 05, AIAA Sr. Member

⁶ Chief Engineer, Orbitec. Space Center, 1212 Fourier Drive, AIAA Associate Fellow

I. Introduction

The objective of this paper is to add assurance that the planning and implementation of the transportation systems required by a space exploration program take maximum advantage of the "lessons learned" from the major space programs of the past decades. The focus of the paper is on what has been learned in the assessment and control of Life Cycle Cost (LCC) from these systems. The Nation has always been interested in achieving LCC control, but the question was "How". The SPST has responded to this challenge and this paper presents a proposed option to greatly improve controlling LCC.

Civil and military applications of Space Transportation have been pursued for 50 years and there has been, and there is now, an even greater need for safe, dependable, affordable and sustainable space transportation systems. Fully expendable and partially reusable space transportation systems have been developed and put in operation. Access to space is technically achievable, but presently very expensive and will remain so until there is a breakthrough in the way we do business.

A critical need for improved communications between the user and the developer led to NASA's Code R and Code M chartering the Space Propulsion Synergy Team (SPST) in 1991. The SPST is a national volunteer organization of government, industry, and university experts in space propulsion, propulsion-related technologies, and other system related technologies. The SPST's first task was to use its member's diversified expertise to develop new engineering management decision-making tools: specifically developing innovative engineering processes in the architectural design, development, and operation of space transportation systems to satisfy the challenging requirements of both the transportation system operators and the payload customers. The SPST established a dialogue among the personnel involved in all phases of the technology, design, development, and operation of a space transportation system.

The major theme of the SPST processes is emphasizes on "developing" the space transportation system "requirements" first (up front) that address and respond to the key objectives desired. These requirements must include the usual system flight performance and the system functional requirements as well as the total infrastructure on Earth's surface, in-space and on the Moon/Mars surface, as appropriate for the application being considered, to determine life cycle costs.

This paper provides a top-level description of the development of these specific innovative engineering and management approaches and processes that were developed. The major change the SPST is proposing is to improve the control of LCC using major cost influencing Program Metrics rather than just controlling the vehicle flight performance and/or mass.

The basic approach is to adapt the management process for weight control that NASA used on the Space Shuttle Program to, in turn, control LCC for space exploration programs. This includes technology, advanced development, DDT&E, development, manufacture, operational, and recycle/disposal plus all the infrastructure cost on Earth, in space, and on non-terrestrial bodies. This will require a major cultural adjustment to the way the U.S. Government in general, and the NASA/aerospace support industry specifically, do business, since LCC - womb to tomb cost - has not been included in the traditional program focus (there has never been focus on trying to develop and control an economically sustainable space exploration program). Commercial enterprises are required to budget and control the LCC of their programs - otherwise they fail and go out of business.

The SPST proposes to address the global problem of budgeting and controlling LCC by assuring that all requirements that address all the major objectives (performance, affordability, safety and sustainability) of the intended program are in place from concept definition through the unique element requirements level. The recommended option to achieve these results is the use of structured engineering management processes to budget and control those functions that are the primary LCC drivers of the program.

II. Background

Because operations costs, both fixed and those related to flight rate, are one of the largest portions of the LCC of a space transportation system, and because they flow from decisions made during the concept definition and design phases, it is useful to examine the current Shuttle Space Transportation System's (STS) costs.

The STS is an approximately 4 billion dollar a year operation. This operation is spread throughout the entire country. It is composed of: producing external tanks (MSFC and Lockheed-Martin); salvaging, recycling and re-filling solid rocket boosters and motors (MSFC, KSC and ATK); providing qualified engines for Shuttle Orbiters (JSC, SSC, Aerojet, and Pratt & Whitney Rocketdyne); providing mission and flight operations (JSC, Boeing, and United Space Alliance); providing ground operations (KSC and United Space Alliance); and providing for a host of assorted other functions from NASA Headquarters to Dryden Flight Research Center and includes coordination with the Air Force for use of the Eastern Test Range. The program represents a complex interaction of many entities. All these functions include work from the most direct (a technician, a flight controller, a line manufacturing employee, etc.) to the most indirect (a manager, a logistics provider, a scheduler, a procurement, finance or human resources officer, etc.).

The ground operations at Kennedy Space Center (KSC), as one of the most visible costs, serves as a representative example to examine in more detail.

Shuttle ground operations at KSC is a roughly 1.4 billion dollar a year operation. It can be divided into eight categories: contractors (Categories 1 – 5); technicians hands-on labor (Category 1); Engineering, Safety & Quality (Category 2); Program Management and Internal Business Functions (Category 3); logistics, depot maintenance and interface to original equipment manufacturers (Category 4); sub-contractors to the primes (Category 5); NASA Program, Project and Institution (Categories 6 – 8); NASA Program and Project Management (Category 6); NASA and contractors center management and operations (Category 7); and, KSC infrastructure (Category 8).

The work ranges from Category 1, which is close-in, hands-on the flight hardware and support equipment at KSC, until, at Category 8, the work is on the base infrastructure, enabling, but farther removed from day-to day flight hardware processing. The indirect business category, often called overhead, lies for the contractor in Category 3, while for the government it lies in Category 7. The engineers and more technical support in Category 2 and 6 work together on a day-to-day basis. The largest workforce under one organization lies in Category 3, as this is the class of work which enables all else. Category 3 includes program management, requirements management, documentation control, configuration control, scheduling, work control including work document generation, interfaces to outside organizations such as other centers, suppliers, and the government as customer. Category 3 also includes internal facing business functions more readily defined as business costs.

The eight KSC detail Categories breakout as follows: Category 1 is \$50M/year; Category 2 is \$150M/year; Category 3 is \$200M/year; Category 4 is \$175M/year (all Orbiter); Category 5 is \$115M/year; Category 6 is \$75M/year; Category 7 is \$300M/year; and Category 8 is \$200M/year as shown in Figure 1.

Plus, there are additional costs of approximately \$150M/year for other Reuseable Solid Rocket Motor / Reusable Solid Rocket Booster (RSRM/RSRB) operations located at KSC but managed by the Marshall Space Flight Center (MSFC). This is over \$1.4 billion dollars a year in funds with an approximate local Florida impact of 12,000 people to prepare, support or otherwise enable the Space Shuttle launches.

It is tempting to assume that a reduction in technician's hands-on labor, by having simpler hardware or a smaller, less complex system, will cascade through all the other support functions. In practice some costs are fixed and relationships are more complex. For example, streamlining a process and eliminating half the hands-on work on a task does not necessarily eliminate half the programmatic and administrative support.

The exploration program can immediately recognize that large sums go towards potentially architecture independent areas of program management (such as contractor Category 3 costs), as well as center functions that have nothing to do with an architecture (such as NASA and contractor Category 4 costs). The contractor business functions that include requirements generation, planning, document preparation, configuration control, scheduling, etc. are by nature connected to technical maturity as measured by demonstrated reliability. A part or sub-system that fails during any phase before launch is a reason for extensive support and/or business functions (Category 2 through 5) to exist, as well as driving as much as 25 to 50 percent of Category 1 dollars.

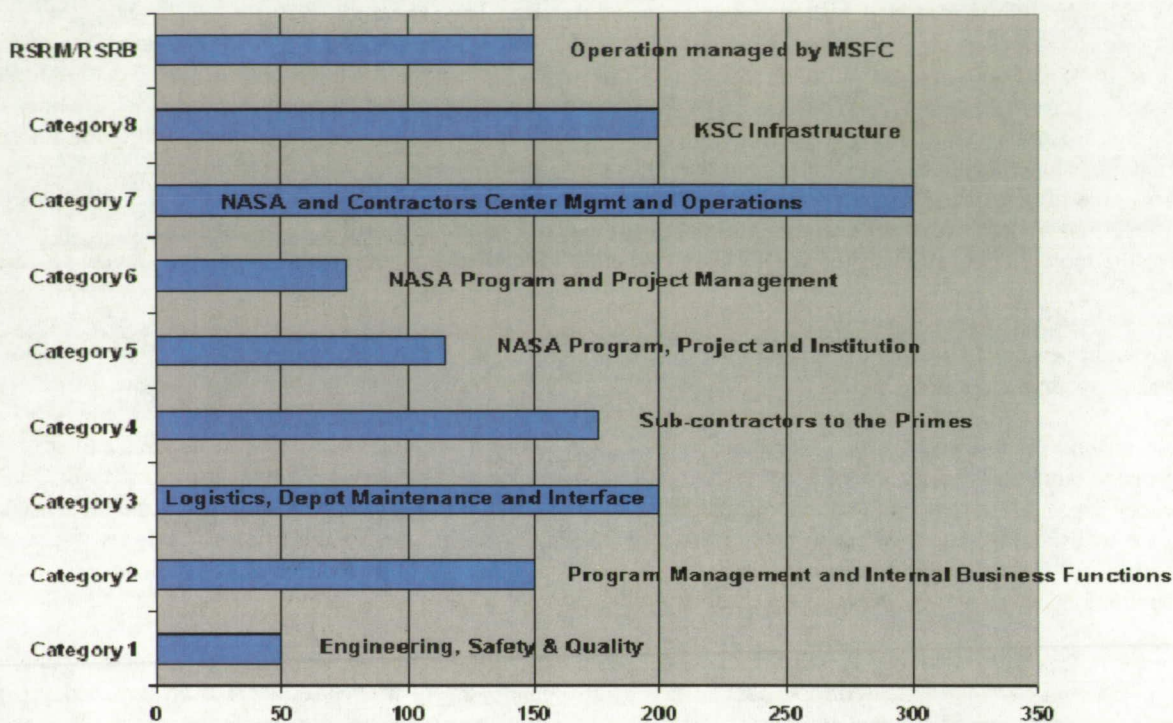


Figure 1. Shuttle Ground Operations Cost at KSC (\$Millions/year)

An unreliable system can never be affordable for human space flight because if the system is unreliable, then the support and business functions will be designed, or persist due to lack of investment, in forms that attempt to “process” in what was not designed into the system (such as by higher volumes of production, and/or higher numbers of test-fail-fix cycles in early design development).

Nonetheless, the indirect support activities, especially Categories 2, 3, 6, and 7, so dependent on information flow judging by their descriptive functions, represent immediate opportunities for affordability gains. Saving even 20% of categories 2, 3, 6, and 7 at KSC alone would save \$150M/year. The extrapolation to the entire \$4B would be on the order of \$500M/year savings. Such an initiative is encouraged starting with an emphasis on business process, such as in engineering, and proceeding to program management, and eventually leading to the implementation of select additional investments in re-engineered processes such as via modern information technology.

Maturity, as manifest in demonstrated reliability, would be an item for generational advance and investment. Initial investments here would include an initiative to quantify where design technology maturity would best ripple through the entire system composed of all Categories, but at the NASA and program level.

III. Problem Statement

This Nation’s ability to provide the development and operation, of safe, dependable, affordable and sustainable space transportation systems is still not being achieved.

During conceptual definition and DDT&E phases, the only major objective (system attribute) controlled in past and present programs by a structured Engineering Management process is performance closure by managing flight systems weight. The present cost estimating process bases cost on flight system dry weight and performs all trade studies optimizing each single flight system function, with no effort to address integrating the total systems

considering all desired attributes. As an example, objectives were set for LCC for the Shuttle, but no Engineering Management processes were exercised to provide control (only the DDT&E cost was tracked). Because the objective was not treated as a requirement, it was not achieved.

The Saturn/Apollo lunar exploration program was terminated early because the recurring transportation cost was not sustainable while supporting the exploration efforts. The reusable Shuttle transportation system was developed to replace the Saturn launch vehicle in an effort to greatly reduce the recurring cost of transportation. Even though the recurring cost of space transportation systems operation was reduced approximately 50 to 60 percent, the reduction was not sufficient and did not approach the target goal.

The major lesson identified from the Saturn/Apollo and Shuttle experience is that much improved, innovative processes must be developed and rigorously applied to effectively control LCC. Any future space transportation system LCC must be controlled throughout the entire design concept phase, DDT&E phase, and its operations phase to provide a sustainable space exploration program. Since a major part of LCC for a space transportation system is the recurring or operational phase cost, this cost must be defined in the design concept phase and rigorously controlled throughout that and subsequent phases.

IV. Historical Shortfalls and Lessons Learned

Historical shortfalls, historical successes and lessons learned all provide an important roadmap to understanding and building an approach to achieving desired program LCC.

Historical programs have been successful in meeting their explicit objectives and their explicit requirements. For example, Saturn/Apollo reached the moon and did so safely within the required schedule, Skylab was completed within its schedule using existing resources, the Shuttle program produced a reusable space transportation system, and quite a number of space probes and landers have been successful in exploring the solar system. Although all these programs have been successful in meeting their major objectives, they have not been successful in meeting all their goals. The common thread in achieving the successes has been the use of structured management and engineering processes to control explicit objectives. The common thread in the lack of success for some of the goals has been the lack of application of these processes to these goals. Objectives that had the processes applied were treated as "requirements" and were achieved, and those that did not, were treated as "goals" and always lost out in trades against "requirements". "Requirements" are "musts" and "goals" are only "wants". And "wants" always lose out to "musts".

The following sections of this paper summarize four studies performed by the SPST that address these LCC issues: (1) Current STS Shortfalls Study, (2) Bottoms-Up Study, (3) Generic Functional System Breakdown Structure Study and (4) Balancing System Safety, Reliability and Maintainability Requirements Study.

V. Current STS Shortfalls Study

To control space transportation system it is necessary to identify the major cost drivers. Design decisions drive the operations costs which then dominate the LCC. The SPST conducted a study that identified the major operations cost drivers.⁽¹⁾

The study reformatted the major lessons learned from previous programs as Technical Performance Metrics (TPMs). To the degree that these are implemented, both the design and the operations aspects of LCC will decrease. Performance and weight can be adversely impacted by the pursuit of these TPM's in some missions and some architectures. Consequently, a balance must be struck between these TPMs and the performance and weight to achieve an acceptable LCC. This balancing should guide the architecture development.

Of the sixty-four TPMs identified in the study, the following eighteen have been determined to be the major cost drivers. The design and operations aspects of LCC are decreased by establishing minimum values of these TPMs consistent with the mission objectives and then flowing down the values of the TPMs as actual requirements. The SPST sought a method to compare many different variables and understand their interrelationship with each other. The tool chosen was a specific Total Quality Management (TQM) tool - Quality Functional Deployment (QFD).

These results were supplemented by the Shuttle Shortfall Analysis study. The procedure is to minimize each of these factors. The factors to be minimized (in order of importance) are:

1. Total number of separate identified vehicle propulsion systems and/or separate stages;
2. Total number of flight tanks in the architecture;
3. Number of safety driven functional requirements to maintain safe control of systems during flight and ground operations;
4. Number of maintenance actions unplanned before or between missions;
5. Number of maintenance actions planned before or between missions;
6. Total number of traditional ground interface functions required;
7. Percent of all systems not automated;
8. Number of different fluids required;
9. Total number of vehicle element-to-element support systems;
10. Number of flight vehicle servicing interfaces;
11. Number of confined/closed compartments;
12. Number of commodities used that require medical support operations and routine training;
13. Number of safety driven limited access control operations;
14. Number of safing operations at landing (for reusable elements);
15. Number of mechanical element mating operations;
16. Number of separate electrical supply interfaces;
17. Number of intrusive data gathering devices;
18. Number of Criticality 1 system and failure analysis modes.

After defining an architecture using these TPMs, a structured engineering management process would then be needed to budget and control the TPMs throughout the design and development phases of any future program.

VI. Bottoms-Up Study

Another study performed by the SPST was a "bottoms-up" analysis which addressed the question of why past programs weren't achieving the desired functional criteria: "what has impeded or prevented the application of good systems engineering and management's successful implementation of the approaches/processes addressed to achieve an affordable LCC."

Candidate technology areas were defined to identify potential technology solutions to fundamental technical and operational barriers or impediments to the development of advanced RLV systems that would be capable of meeting program cost, safety, and responsiveness goals. Workshop prioritization results and the technology areas recommended for investment consideration were documented that apply to advanced propulsion technologies for potential future applications to in-space robotic missions, including high thrust and low thrust earth orbital, lunar and planetary missions.

The candidate technology areas identified by the bottoms-up assessment process, the criteria used for prioritization of these areas, the workshop participants, and the workshop process and procedures were summarized and conclusions drawn based on the results.⁽²⁾

The SPST's approach emphasized traceability to second generation systems and technologies. Structured brainstorming was used to identify technologies and conceptual solutions that directly address advanced reusable launch vehicle (RLV) system design criteria such as those developed over the past several years by the SPST. The current Space Shuttle systems and operations practice was used as the pivot or reference technology base against which all the candidate technologies would be assessed for prioritization in the workshop. A white paper briefing was prepared for the reference Shuttle technology base. The results were summarized in 26 candidate technologies organized into six selected categories as described below.

Vehicle Health Monitoring (VHM) Technologies

1. Critical Failures Identification - 100% IVHM data to identify all credible critical failures in adequate time to implement corrective action or abort.
2. Systems Health Verification - Provide totally integrated and automated functional health verification for all systems.
3. Automated Predictive Maintenance - Automated predictive maintenance capability designed in as part of component development.
4. Preflight Checkout - IVHM performs all preflight checks; visible check only required.

Margin Technologies

5. Air-breathing Main Propulsion - Develop all air-breathing concept (including ejector rocket, subsonic LACE, combined cycle) system alternatives that have benefit measured in payload to dry weight ratio and with an acceptable level of complexity. Develop as an integrated solution using comparable (to rocket) techniques.
6. Lightweight Subsystems - Develop lighter weight propulsion subsystems.
7. High Performance Subsystems - Develop higher performance propulsion subsystems (higher I_{sp} , lower temperature, lower pump pressure, longer life subsystems).

Operations Technologies

8. Elimination of Support Systems - The development of critical technologies eliminating the need for ground support systems; e.g., self-contained engine valve and TVC actuators, eliminating requirement for distributed pneumatic and hydraulic systems.
9. Elimination of Turnaround Operations - Develop technologies that eliminate operations associated with turnaround of propulsion system (no purging or cleaning operations).
10. Leak Free Joints - Develop leak free joints in propulsion systems (including H_2).
11. Simplified Mating Operations - Develop simplified mating operations technologies (automated alignments, fluid connections, and interface checks).
12. Passive Aero Solutions - Develop technologies to utilize passive aerodynamics to minimize venting and purging requirements and eliminate the use of closed compartments.
13. Single Main Propellants - Use same main propellants in multiple stage vehicles.
14. Wireless Communication - Develop and mature wireless communication technology required to eliminate element-to-element and element-to-ground umbilicals.
15. Cleaning Alternatives - Develop environmentally acceptable materials and cleaning alternatives that do not substantially compromise performance.
16. Cryogenic Conditioning - Minimize the need for cryogenic conditioning to start vehicle engines.

Safety Technologies

17. System Failures Tolerance - Develop the ability to tolerate credible system failures (e.g., contain an engine blade failure).
18. Pyrotechnics Elimination - Eliminate all pyrotechnic devices in favor of highly reliable, reusable mechanical devices.

Thermal Control Technologies

19. Active TPS Elimination - Develop use of ultra high temperature ceramics to eliminate active TPS and explore a wider range of TPS technologies in an operational environment including transpiration cooling, ablatives, heat sinks, passive aero techniques (search for fundamental thermodynamic technologies).
20. Active Thermal Control Elimination - Develop generic technologies that eliminate active thermal management systems.

Technologies to Reduce Number of Systems

21. All Rocket Cycle - Use of all rocket cycle propulsion technologies.
22. Integrated Propulsion/Thermal/Power – Use of technologies to integrate Reaction Control System (RCS), Orbital Maneuvering System (OMS), Main Propulsion System (MPS), Thermal Management, and Power Generation into one system.
23. Integrated RCS/OMS/MPS - Use of technologies to integrate RCS, OMS, and MPS into one system.
24. Integrated RCS/OMS - Use of technologies to integrate RCS and OMS into one system.
25. Residual Gases Utilization – Component development to allow use of unusable residual gases for propulsion functions.
26. MPS Low Thrust Mode for OMS - Use of a very low thrust MPS mode for the OMS propulsion function.

Prioritization Criteria

Over the past several years the SPST has developed and weighted a set of technical and programmatic criteria for use in assessing and prioritizing candidate propulsion and propulsion-related technologies for the development of advanced RLV systems. The criteria were weighted using a structured Quality Function Deployment (QFD) process supported by NASA input.

The SPST workshop evaluation team assessed and scored each candidate technology area against each of the technical and programmatic criteria. For each candidate technology area, the evaluators considered the question: "What is the potential of this technology area compared to current Shuttle technology or practice to contribute to achieving the given criterion for advanced RLV systems?"

Global Priorities for Decreasing Costs

A separate assessment at the workshop of the candidate technology areas for their potential specifically to reduce the cost of advanced RLV systems indicated that the Automated Predictive Maintenance, the Elimination of Turnaround Operations, and Systems Health Verification are high priority technology areas. These are followed in priority by a number of other IVHM, Operations, and technologies that reduce the number of systems to be developed and operated.

Combining all Global Data

The results of combining the separate global technical, programmatic, safety, and cost results with equal weightings (25% each) indicated that the IVHM technologies had high priorities. The data also indicated that the technical and programmatic influences placed strong priority on reducing the number of systems, improving operations, and increasing system margins.

Summary Overall Bottoms-up Study

The following conclusions were drawn from the global prioritization results of the workshop:

1. The results of the global processing of the data across all 25 technical and 19 programmatic criteria indicate that the highest leverage propulsion and propulsion related technologies are those that:
 - (1) Reduce the number of systems to be designed, developed, tested, and operated;
 - (2) Increase system margins; and
 - (3) Simplify thermal control of the flight vehicle.

IVHM and Operations technologies are important but are prioritized lower based on the given technical and programmatic criteria.

2. The results of the team's two additional assessments of the 26 candidate technology areas for their potential to specifically increase safety and decrease costs showed that the IVHM technologies (particularly Automated Predictive Maintenance and Systems Health Verification) are of high priority.

These data also showed that several Operations technology areas are important to reduce costs, including particularly the Elimination of Turnaround Operations, Elimination of Support Systems, Simplified Mating Operations, and the Use of Single Main Propellants.

In addition, the reduction of the number of systems will be important, particularly the use of Integrated Propulsion/Thermal/Power systems and Integrated RCS/OMS/MPS designs.

3. Combining the results of the baseline technical and programmatic priorities with the separate safety and cost assessments shows that overall the IVHM technologies are highest priority for investment.

4. Most of the technology solution areas identified by the SPST that address the impediments or barriers to achieving advanced RLV system goals tend to not be very exotic or exciting technologies. However, they address areas where large technological improvements are required. Also these technology areas tend to be crosscutting and are required by most envisioned system concepts. It is believed that detailed studies would show strong benefit-to-investment cost ratios for most of the identified high priority / high leverage technology areas.

Overall results are very stimulating and deserving of more in-depth attention. For example, it was found that there are several reasons for the impediments: lack of overall integration (stove-piping or optimizing at the single function level), inappropriate starting technology level, the lack of sufficient Engineering Management processes, and that many of the systems engineering requirements (needs), were "boring", not stimulating (not sexy). This indicates that major improvements in discipline must be rigorously imposed on the system engineering and design processes by the program managers and the chief systems engineers.

VII. Generic Functional System Breakdown Structure Study

The LCC of the entire exploration architecture consists of the development and acquisition costs and the operations and disposal costs. For space transportation systems that will be in place for a long time, typical for U. S. space systems, the operations and disposal costs will dominate the LCC. New programs must be "sustainable", e.g., they must be within their specific budget and within their yearly budget caps both during procurement and throughout their long operating life. For this to be achievable, operability must be designed into the architectures and elements from the very beginning. Failure to achieve the budgeted transportation costs will squeeze the exploration budget and has the potential to severely impact the sustainability of the entire program.

The operations and disposal costs are determined, often without specific planning, during the system architecture definition and the individual element developments. It has been estimated that 80 percent of the design decisions are irreversibly made in the system architecture definition and the individual element development design phases.

It is very difficult during architecture definition to balance and minimize, or even compare, the overall LCC, including both development and acquisition costs and operations costs. This is primarily due to the lack of full definition of all the necessary functions of the potential architecture options. Different options have different levels of definition but still must be compared. And often not all of the supporting elements necessary for each architecture are identified at all. It is also very difficult during element developments, primarily due to schedule and budget pressures, to maintain the design discipline to ensure that operations costs will not escalate due to design decisions addressing immediate design, weight, performance, or development problems. The emphasis in design is to get the job done (i.e., achieve weight and performance) within the schedule and hopefully within the budget. When problems must be solved there is seldom the budget or schedule available to properly consider the operations cost impacts of the design options examined. Consequently, the future operations and disposal costs escalate to improve the currently incurred development costs.

Only if overall LCC, including operations, is a required metric, co-equal with weight and performance, can the LCC have any real chance of being controlled. In the past, goals for LCC were not a contractual requirement that was flowed down to the individual element developments with rewards and penalties equal to those for weight and performance. Consequently, LCC goals simply have not been met.

The SPST has studied this problem since 1991 and has developed approaches and tools to address the problem. The Shuttle Shortfall Analysis study, the "bottoms-up" study, and the QFD determination of the cost drivers have clearly shown that the most important means to control LCC is to fully and clearly define the requirements of the program. The requirements must address both the flight objectives (as is commonly done) and the functional objectives including the entire support infrastructure. These requirements must be allocated and flowed down throughout the entire architecture. Requirements not flowed down, become "goals" and may not be met.

It is necessary to identify all the requirements and elements of an architecture at the beginning of a program if the LCC is to be controlled. The SPST has developed a methodology utilizing a Functional Breakdown Structure (FBS) to accomplish this difficult task.

The FBS is a structured, modular breakdown of every function that must be addressed to perform a generic mission and is also usable for any subset of the mission. It is not tied to any particular architectural implementation because it is a listing of the needed functions (not elements of the architecture). The FBS provides a universal hierarchy of required functions, which include ground and space operations as well as infrastructure – it provides total visibility of the entire mission. This is a new approach that will provide full accountability of all functions required to perform the planned mission. It serves as a giant check list to be sure that no functions are omitted, especially in the early architectural design phase.

A significant characteristic of a FBS is that if architecture options are compared using this approach, then any missing or redundant elements of each option will be identified. Consequently valid LCC comparisons can be made. For example, one architecture option might not need a particular function while another option does. One option may have individual elements to perform each of three functions while another option needs only one element to perform the three functions.

Once an architecture has been selected, the FBS will serve as a guide in development of the work breakdown structure (WBS), provide visibility of those technologies that need to be further developed to perform required functions, and help identify the personnel skills required to develop and operate the architecture. It also will allow the systems engineering activities to totally integrate each discipline to the maximum extent possible and optimize at the total system level, thus avoiding optimizing at the element level (stove-piping). In addition, it furnishes a framework which will help prevent over or under specifying requirements because all functions are identified and all elements are aligned to functions.

The SPST has developed a preliminary space transportation system FBS including supporting elements for a manned exploration mission.⁽³⁾

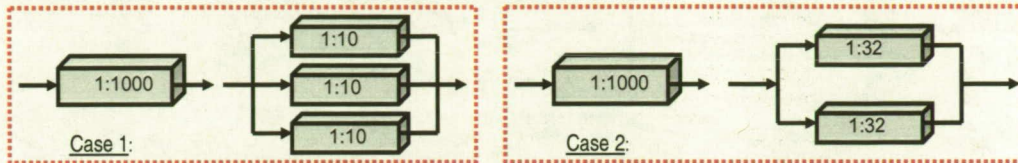
VIII. Balancing System Safety, Reliability, and Maintainability Requirements Study

One design technique for increasing mission reliability emphasizes increased redundancy. However, it should be noted that this technique, i.e., increasing reliability through redundancy, often results in increasing the maintainability burden.

A notional example that demonstrates how added redundancy, inserted in a design to increase reliability, may also increase the maintainability burden is shown in Figure 2. The example cited compares a notional triple redundant string (Case 1 left) with a dual redundant string (Case 2 right). The examples use a mission reliability goal of 0.999. Case 1 results in a 300:1 added burden on maintainability, whereas case 2 results in a 60:1 added burden. The resulting outcome on recurring cost is different – the added parts count of Case 1 increases cost compared to Case 2. A thorough appreciation of the coupling of maintainability and reliability must be held throughout the design phase, and design teams must strive for low parts counts in order to meet critical maintainability objectives.

The Coupling of Maintainability And Reliability (Redundancy - Case)

Techniques for increasing mission reliability (increased redundancy) should be used only to achieve safety goals desired above and beyond that reliability required to produce the lowest life cycle cost avoiding added maintainability burden.



Simple Example Comparisons

(Each with common reliability/safety requirements, but very different maintainability burdens and recurring cost outcomes)

Case 1: Reliability objective set = 0.999 with single string component two orders-of-magnitude more reliable than using three parallel components

- 1:1000 = 3 of 1:10 in parallel = 0.999 reliability objective (Reliability = $1 - 1/10^3 = 0.999$)
- **Result:** 300:1 added burden on maintainability for triple redundancy vs. single higher reliability component

Case 2: Seeks to find a dual redundant solution and meet the Reliability objective set = 0.999

- 1:1000 = 2 of 1:32 in parallel = 0.999 reliability objective (Reliability = $1 - 1/32^2 = 0.999$)
- **Result:** 60:1 added burden on maintainability for dual redundancy vs. single higher reliability component

Figure 2. Coupling of Maintainability and Reliability: Sample Case Study

Individual design teams often seek to optimize their system, and system engineering staffs often force this onto them via the requirements definition process. Design teams must first and foremost meet their specifications (be compliant). Program management must look at the total vehicle, its operations, its future upgrade paths as a whole system, and be disciplined enough to appreciate the necessity of coupling maintainability and reliability goals with performance goals to prevent independent subsystem level optimizations from collectively adversely affecting LCC.

As an example, even though the Shuttle initial design considerations emphasized performance, maintainability goals were also set, but inadequate internal discipline was exercised and a high performance, but also high maintenance cost, flight system was the result. Recurring costs and maintenance costs must be reduced and an essential factor in that process is the introduction of fewer, but more highly reliable, components. The inevitable "growth in parts count" that results from "highly redundant" design approaches often leads to maintenance intensive designs.

If the element or component reliability requirements to achieve the desired minimum maintainability burden become prohibitive, then the efforts must focus on other methods of reducing the parts count. The reduction in parts count may be accomplished through improved functional integration of systems, restructuring redundant combinations to a minimum, and using the highest element reliability possible.

The "maintainability burden" is a major driver of recurring cost. Often a key element in the recurring cost burden is a direct function of the number of parts. Part counts increase when the reliability of the selected parts is not sufficient to meet safety needs and redundancy is instituted to achieve reliability goals. Part counts are also increased by the lack of functional systems integration. To achieve recurring cost objectives, highly reliable parts must be used in the design, which in turn leads to lower repair requirements that will drive down the maintainability requirement. Figures 3 and 4 show these effects.

Notional System Cost Dependence on Reliability, Maintainability, and Tradeoffs

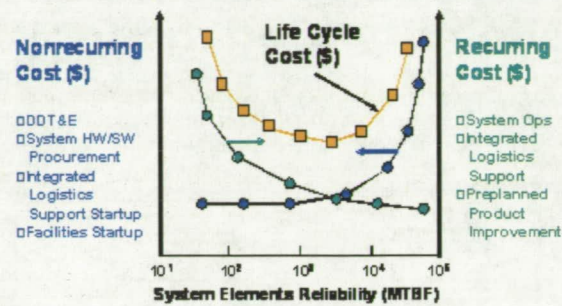


Figure 3. Flight System Cost Dependence on Reliability, Maintainability

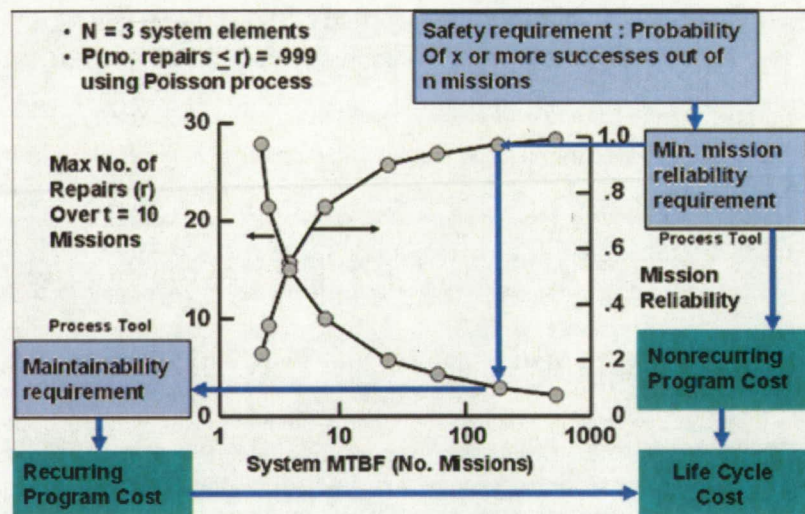


Figure 4. Mission Reliability, Repairs over Flight Rate Period and MTBF

Thus it is imperative to conduct early technology development programs to achieve the availability of high reliability parts.

Achieving this balance of design life requirements with safety and maintainability objectives requires a process such as that shown in Figure 5 for developing and balancing quantitative safety, reliability and maintainability requirements. Achieving the appropriate balance among these factors to achieve low recurring cost requires a thorough understanding of subsystem element reliability, subsystem element fail rate and the number of serial system elements.

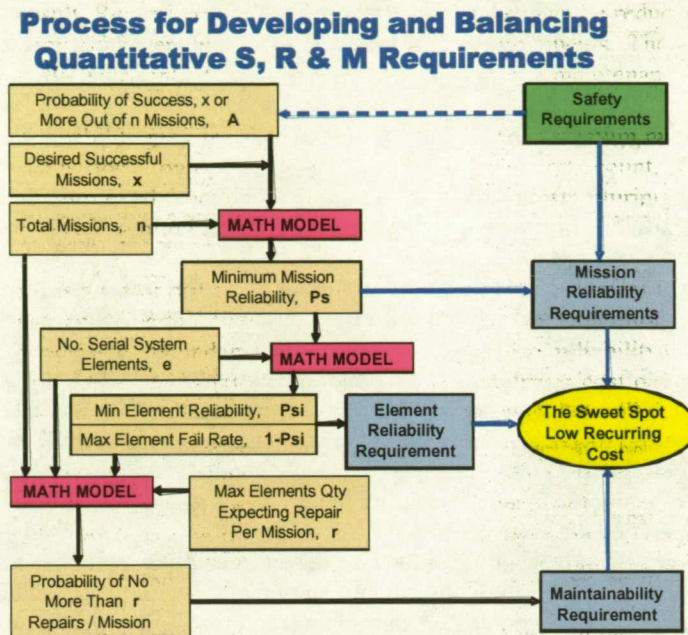


Figure 5. Process for Developing and Balancing Quantitative Safety, Reliability and Maintenance Requirements.

IX. Conclusions and Recommendations

To take maximum advantage of the "lessons learned" from the major space programs of the past decades, this paper has reviewed top-level results of a selected number of studies and analyses that have been conducted by the SPST. These directly address the "lessons learned" from previous transportation systems.

These extensive studies by the SPST have shown the need of LCC control, but introduction has been a continuing problem as new programs have been implemented without such effective control. The SPST is recommending that the aerospace industry adopt the proven methods of controlling weight and performance and apply them to controlling cost.

Insight gained from performing the shortfalls assessment stresses the need to perform optimization at the total systems level and not at the subsystem level (stove-piping). The SPST has also developed a new approach for formulating "requirements" that will provide full accountability of all functions required to perform the planned missions. The approach is to develop a top-level functional systems breakdown structure, FBS, with modular subsets that may be utilized as a basis for defining the desired "functional requirements" in any system. This process will then serve as a guide in development of the work breakdown structure (WBS), provide visibility of those technologies that need to be developed, and help identify the personnel skills required to develop and operate the space transportation system.

The functional breakdown structure (FBS) should be used to ensure that architecture options are compared fully and validly. Once the architecture is chosen that can meet the performance and LCC requirements, then the LCC and performance requirements must be allocated and flowed down to all lower tiers. The FBS should be used for this. LCC, or an LCC allocation, must be a requirement at each of the lower tiers.

Once the performance and LCC requirements have been flowed down, an addition to the engineering management processes must be made to add a new structured engineering management process modeled on the processes used in the past to successfully manage, track, and control weight. This process must be enforced by the program managers

throughout the design, development, production and operation of the program. The process should include contractual rewards and penalties for LCC compliance where contracting methods are exercised just as they are used for performance and weight. The objective is to establish LCC as a true requirement and to not let it become merely a "goal".

In summary the SPST recommendations are:

1. Make LCC, including operations and disposal, a required metric, co-equal with weight and performance, and flow it down to the individual element developments with rewards and penalties in the same manner as used for weight and performance control.
2. Define architectures using the TPMs described earlier in this paper and implement a structured engineering management process to budget and control the TPMs throughout the design and development phases of the program.
3. Fully and clearly define the requirements at the program beginning.
 - a. Use a functional breakdown structure (FBS) as a tool to accomplish this full definition.
4. Use requirements and engineering management control processes to control major operational technical functions that greatly influence LCC.
5. Balance the safety, reliability, and maintainability requirements to provide controls on recurring maintenance burden to provide operational effectiveness and LCC control:
 - a. develop a thorough understanding of the cost dependence on reliability and maintainability tradeoffs;
 - b. develop a thorough appreciation of the coupling of maintainability and reliability;
 - c. use a methodology or process for developing and balancing quantitative safety, reliability and maintainability requirements.

Acknowledgments

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